

# Experiences with the critical review process of aluminium LCI data

Walter Klöpffer

Received: 7 June 2008 / Accepted: 13 December 2008 / Published online: 20 March 2009  
© Springer-Verlag 2009

## Abstract

**Background, aim, and scope** This paper summarises the critical review process according to ISO 14040/44 performed for the European Aluminium Association (EAA), Brussels. Scope of the review was a life cycle inventory (LCI) project, aiming at providing the life cycle assessment (LCA) community with reliable generic data relevant for the European aluminium market, including the production of aluminium ingot either from primary aluminium or from recycled aluminium and the fabrication of semi-finished products, i.e. sheet, foil or extrusion fabrication from aluminium ingots.

**Main features** Critical reviewing according to ISO 14040 and 14044, although described formally in the standards, evolved essentially via ‘learning by doing’. This special review has been conducted as a critical review by one external expert. Since no comparative assertions are to be expected from the results obtained, a critical review according to the panel method (at least three reviewers) was deemed not to be necessary. The review process was interactive and took about a year (March 2007 to April 2008). The full review report is printed in full length at the end of the published LCI data report.

**Results** The report continues the tradition of the former reports but offers new aspects. The main change refers to the use of new software for data handling (GaBi 4.0 replacing the formerly used LCA-2 based on BUWAL data), including generic data for ancillary processes and inputs for the energy

model. The LCI results, therefore, cannot be compared exactly with the data of the previous reports. There is no disconnection, however, so that trends can be observed and discussed with some precaution. The main trend with respect to energy and emissions is one of slow but steady improvement. A main methodological improvement with regard to the former projects is the new energy model, especially with regard to imported primary aluminium.

**Discussion** There was some discussion about the term ‘waste’ when it is put outside the system boundary together with the resulting emissions. According to the author’s opinion, there are at least three types of waste: (1) waste to be reused or recycled—this waste stays within the technosphere and, thus, within the system boundaries of a typical LCA; (2) waste to be collected and removed legally by incineration, controlled landfilling or composting—this waste stays within the technosphere, too; only the emissions of the waste removal processes (CO<sub>2</sub>, CH<sub>4</sub>, organic contaminants to ground water, leached metal ions to ground water, etc.) escape into the environment if not collected properly; (3) waste thrown away, e.g. by littering, illegal dumping, burning, etc.; this waste ends up in the environment if not collected. There was a time when solid waste in LCA (if landfilled) was considered as an ‘emission into soil’. This is only true for illegal, uncontrolled land filling. Controlled landfilling is a kind of process and belongs to the technosphere as long as it is controlled. EAA envisages to include appropriate data in future updates (incineration is already included).

**Conclusions** According to ISO 14040, “The critical review process shall ensure that: the methods used to carry out the LCA are consistent with the international Standard; the methods used to carry out the LCA are scientifically and technically valid, the data used are appropriate and reasonable in relation to the goal of the study; the interpretations reflect the limitations identified and the goal of the study;

---

Responsible editor: Gerald Rebitzer and Jörg Schäfer

---

Special Issue “Life Cycle Performance of Aluminium Applications”

---

W. Klöpffer (✉)  
LCA Consult & Review,  
Am Dachsberg 56E,  
60435 Frankfurt am Main, Germany  
e-mail: walter.kloepffer@t-online.de

the study report is transparent and consistent.” These five points can be confirmed with a few restrictions. With regard to the first item, consistency with ISO 14040/44, there is a formal lack of a section ‘interpretation’. It was also discussed that the study is not a full LCA, but the standard allows for LCI studies. As such, the study conforms to ISO. The methods used in data collection and modelling are described clearly and correspond to the state of the art. They should be published and become standard for generic data collection.

**Perspectives** It is assumed and recommended that the process of continuous improvement (both technological and relating to data collection and modelling) will continue in the following years. However, since raw aluminium production is faced with thermodynamic limits, it is proposed to rethink the whole aluminium system, which is based on a century-old technology and to conceive bold new routes, especially aiming at a further increase of renewable energy use and further improving recycling in countries with deficient waste collecting systems. The use of heavy fuel oil in alumina production should be discouraged.

**Keywords** Aluminium · Critical review · Generic data · ISO 14040 · Life cycle inventory · LCI

## 1 Aluminium, LCA and sustainability

Aluminium, the central material of this special issue of *The International Journal of Life Cycle Assessment*, is a priori disadvantaged due to the first law of thermodynamics: The enthalpy ( $\Delta H$ ) needed to reduce alumina ( $\text{Al}_2\text{O}_3$ ) to aluminium (Al) sets a limit to any endeavour of reducing the (electrical) energy demand below this barrier set by nature. On the other hand, aluminium has properties that are useful not only under technological aspects but also, if used properly, even under environmental and sustainability aspects. Advantages are, for example, low density (leading to light weight products), corrosion resistance (leading to longevity of products, even if used outside), oxygen and water vapour barrier function (for instance to protect food or pharmaceutical products), generally easy collection (leading to high collection rates) and—as most metals—quantitative recycling of professionally collected Al scrap. Light weight products, for instance, if used in transport, can reduce the energy needed for traction considerably and thus compensate, or even overcompensate, the energy needed in the production of the raw aluminium (Bertram et al. 2009; Boin and Bertram 2005).

Proper use of Al can contribute to a sound environmental development but only if the alternatives are compared in a quantitative way and if the aluminium-based solution is better than (or at least equal to) other solutions. Here is where the life cycle assessment (LCA) comes into the play.

Always since the times of the early ‘proto-LCAs’ (Klöpffer 2006), aluminium was in the focus of the LCA community, and not always in a friendly way, mostly due to the energy data (the main aggregation in the early time). It is laudable that the aluminium associations took up the challenge and started early, actually during the first round of standardisation (ISO 1997-2000), providing the Al-producing, Al-using and Al-recycling industry as well as LCA practitioners with original data. These data cover most environmental aspects (Chapter 2). We understand today that there are few materials, if any, which are per se environmentally bad (or good); it rather depends on the type of use and the whole life cycle, including the end of life phase. It can be said that LCA has contributed to this understanding and ended the ‘black and white’ controversies.

There is another aspect of growing importance: The environmental behaviour of a product, process or material is only part of its sustainability, which is the ultimate aim of any responsible product development. Certainly, a quantitative assessment of sustainability has to follow the life cycle concept in which the already standardised LCA will play a leading role towards the life cycle sustainability assessment of products (Klöpffer 2008b). Life cycle costing (Hunkeler et al. 2008), the quantification of the second, economic, pillar of sustainability, is available as a draft SETAC guideline (SETAC 2008). The third pillar—societal life cycle assessment—is still under development but progressing rapidly (Hunkeler 2006; Jørgensen et al. 2008). Thus, the contribution of a material to sustainability will not only depend on its environmental life cycle performance, as quantified by LCI/LCA, but also on economic and social aspects to be evaluated in a life cycle perspective.

The life cycle of aluminium products has often been treated in this journal, starting 1997 with one of the rare reports on critical reviewing of LCAs (Fava and Pomper 1997). Aluminium window frames were used as an example for economic allocation by Werner and Richter (2000), see also Guinée et al. (2004). Very recently, crediting aluminium recycling was treated by Frees (2008) and recycling of aluminium cans by Gatti et al. (2008). These examples show that aluminium has been a hot topic in the LCA community. The updated data published now by European Aluminium Association (EAA 2008; Leroy 2009) will therefore be highly welcome.

## 2 The role of EAA in providing data on the aluminium life cycle

EAA started to collect data for the inventory in the 1990s. The first data collection, comprising the reference years 1991/1992 (and 1994) appeared in 1996. This first report

was followed by a second one in 2000, with 1998 as reference year (EAA 2000), and by an update report in 2005, reference year 2002 (EAA 2005). The present EAA report (with reference year 2005; EAA 2008) is thus the fourth one.

The data collected, updated and published were offered to and accepted by the LCA community, including the LCA software and database producers. Generic (or background) LCI data are perfectly suited for commodities to be used in assessing end products when the exact origin of the material(s) used in a specific product is not known but only the market (in this case Europe). The present data set is being partly included into the European (EU) LCA database (Joint Research Center Ispra, <http://lca.jrc.ec.europa.eu>) and will foster the (already strong) European position in generic data collection and provision.

The three first EAA data collections were reviewed and ‘certified’ by Ian Boustead, life cycle pioneer and data collector since the 1970s (Boustead 1996; Boustead and Hancock 1979; Klöpffer 2006). Our thanks are also due to him.

### 3 The critical review process

#### 3.1 General remarks about the critical review process in LCA

The critical expert review was first introduced by SETAC in the LCA ‘Code of Practice’ in 1993 (SETAC 1993) as an interactive process in order to increase the quality and the credibility of LCA studies. This element of LCA was taken over by ISO in the first series of standards (ISO 1997-2000) and sharpened with regard to the possible misuse of the method, especially in comparative LCAs of competing product systems. In the slightly revised ISO LCA standards of 2006 (ISO 14040 and ISO 14044), two kinds of critical reviews are proposed: a review by an external or internal independent expert or a review by ‘Interested parties’, a panel of at least three experts whose chair may include further interested parties, e.g. governmental representatives, members of industrial associations or competitors. The size of the panel depends on the goal and scope of the study and on the financial possibilities. Confidentiality plays a major role, too. The critical review is optional, except if the study is intended to support comparative assertions and is intended to be made available to the public. In this case, only the panel method is allowed by a clear ‘shall’ in the standards. Since no comparative assertions will result from the EAA data collection, this possibility has not been considered in this study.

There is not much literature about the critical review process (some exceptions being Klöpffer 1997b, 2005) so that the relevant sections of the ISO standards have to be

interpreted case by case. A useful distinction between different ways of performing the critical review (internal or external expert, panel) is the distinction between an interactive or accompanying review, as proposed by SETAC (1993), and a review ‘a posteriori’, i.e. after completion of the LCA study. ISO does not prescribe one or the other, but SETAC strongly favours the interactive mode, which indeed has more advantages than disadvantages (Klöpffer 2005). In the present case, it was decided that the critical review is to be performed in the interactive mode by a single external and independent expert, the author of this article.

#### 3.2 Procedure of the critical review

The review procedure started with a kick-off meeting on March 7, 2007 in Brussels, where also the following meetings took place. In this meeting, it was agreed upon that the review will be performed as a critical review according to the revised ISO standards 14040 (2006a) and 14044 (2006b). In these standards, LCI studies, consisting of a goal and scope chapter, life cycle inventory (LCI) and interpretation, are included and can be accepted under the provision that such studies are not called LCA. They are distinguished from a full LCA study mainly by the absence of the life cycle impact assessment phase (LCIA). Clearly, in the present study, there are further restrictions, since the manufacture of the final products and the use phases had to be left out for obvious reasons. The other important life cycle stages of Al (mining, alumina production, primary aluminium by electrolysis, melting and remelting, as well as recycling) are treated and together can be considered as a truncated LCI. The review was conceived as a review by an independent external reviewer according to ISO 14044, section 6.2. The meetings 2 to 6 dealt with the data collection results of the life cycle stages mentioned above.

The final (seventh) meeting took place April 17, 2008. Main topic was the discussion of the draft final report and comments made by the reviewer with Christian Leroy (EAA’s system analyst) and Bernard de Gélas (external LCI consultant).

#### 3.3 About the environmental profile report

##### 3.3.1 General

The report stays in the tradition of the former reports but offers new aspects. The main change refers to the use of new software for data handling (GaBi 4.0<sup>1</sup> replacing the formerly used LCA-2 based on BUWAL data), including generic data for ancillary processes and inputs for the

<sup>1</sup> <http://www.gabi-software.com>

energy model. The LCI results can therefore not exactly be compared with the data of the previous reports. There is no disconnection, however, so that trends can be observed and discussed with some precaution. The main trend with respect to energy and emissions is one of slow but steady improvement. A main methodological improvement with regard to the former projects is the new energy model, especially with regard to imported primary aluminium (36%; EAA 2008; Leroy 2009).

The LCI is presented in the form of building blocks corresponding to the stages of the life cycle in a logical order. It is worth mentioning that this LCI study is more than a ‘cradle-to-factory gate’ study, as most generic data sets, but comprises the most important end-of-life phase, recycling. This phase is of outmost importance for many Al products, since only a very efficient recycling can reduce the thermodynamically caused high energy demand of aluminium production.

The coverage is excellent for the large industrial installations (e.g. primary aluminium production) and, as to be expected, less so if small companies dominate (as in recycling). Data consolidation plays a major role in raw data treatment and has been solved in a convincing manner. The geographical coverage includes EU 27 + Norway, Iceland and Switzerland. Due to the inclusion of Al imports, the actual geographical system boundary is much larger, or even global, if the mining and alumina production is considered.

LCIA indicator results are included in this report, which do not belong to LCI data sets. It is stated, however, that these results are shown for purely informative purposes, not to be used for comparisons. Only the cumulative energy demand can be considered as belonging to LCI, as a—very useful—relict of ‘proto-LCA’ (Klöpffer 2006) inventory aggregation. It gives additional information compared to other often energy-related impact categories, as climate change and depletion of fossil energy resources and encourages energy saving independent of its origin (Klöpffer 1997a; VDI 4600 1997).

### 3.3.2 Details

The report is structured in a logical way, starting with a description of the aluminium life cycle (1), a project description (goal and scope) (2), primary Al production including the bauxite mining, alumina production and electrolysis with electricity model (3), sheet production (4), foil production (5), extrusion (6) and Al recycling (7). Chapters 3–7 constitute together the elements of the truncated LCI. It should be mentioned that there is no full LCI (and, hence, no full LCA) of any commodity, since for doing so, all uses would have to be modelled: an evidently impossible task. What is presented in these chapters are the

data and sub-system descriptions including flow charts, tables and figures to help the reader through the masses of information. A separate chapter ‘Interpretation’, as requested by ISO 14040 (2006a), is missing, but relevant information about data quality can be found throughout the report in the relevant chapters.

The recommendation of the allocation procedure supported by the metals industry (against the ‘recycled content approach’; Declaration by the Metals Industry on Recycling Principles 2007) and confirmed by Frees (2008) is understandable from EAA’s point of view but in no way binding for the data users: The kind of allocation used depends on the goal and scope in each individual LCA. The statement (Declaration by the Metals Industry on Recycling Principles 2007) is useful, however, since it points to the special role of metals in recycling (high-quality scrap leading to secondary materials often undistinguishable from primary ones) and will be followed by many LCA practitioners.

The horizontal aggregation procedure used for calculating the European averages (2.3) is laudable, since it facilitates the modular approach of LCI/LCA for the users.

There was some discussion about the term ‘waste’, as used in Fig. 2.2 (EAA 2008) where it is put outside the system boundary together with the emissions into the environment. In my opinion, there are at least three types of waste:

1. Waste to be reused or recycled: this waste stays within the technosphere and, thus, within the system boundaries of a typical LCA
2. Waste to be collected and removed legally by incineration, controlled landfilling or composting: this waste stays within the technosphere, too; only the emissions of the waste removal processes (CO<sub>2</sub>, CH<sub>4</sub>, organic contaminants to ground water, leached metal ions to ground water, etc.) escape into the environment if not collected properly
3. Waste thrown away, e.g. by littering, illegal dumping, burning, etc.; this waste ends up in the environment if not collected.

There was a time when solid waste in LCA (if landfilled) was considered as an ‘emission into soil’. This is only true for illegal, uncontrolled land filling. Controlled landfilling is a kind of process and belongs to the technosphere as long as it is controlled. EAA envisages to include appropriate data in future updates (incineration is already included).

LCI data for bauxite mining were taken from the International Aluminium Institute (IAI) datasets and do not contain information about land occupation (area × time), a minimum inventory input requirement for land use impact assessment in LCA. EAA intends to complement the dataset in the next round, although it seems difficult to obtain reliable data on land occupation during mining. Since bauxite occurs in relatively thin layers, which are



peeled of mechanically, large areas of land are deprived of the soil cover and recultivated later. The importance of ‘land use’ as an impact category has increased in recent years, partly as a proxy for biodiversity (Milà I Canals et al. 2007). In connection with land use, also the ‘overburden’ will be addressed; this is not a major problem in bauxite mining but relevant for recultivation.

The use of heavy oil (high sulphur content) reported to be used for alumina production, although reduced in recent years, is certainly an area for improving the environmental performance of the Al system. As in the case of sea transport, the use of heavy oil should be avoided.

The change in power grid from UCPTE to the EU-25 grid mix due to the geographical extension and the software change should have been secured by a sensitivity analysis for which there was not enough time. Some changes are discussed in the text, however.

Reporting of polycyclic aromatic hydrocarbon and benzo [a]pyrene data from smelters is laudable. Toxic emissions are sometimes ‘forgotten’ by generic data providers. Polyfluorinated compounds are included as important greenhouse gas emissions of the smelters; they have been reduced in recent years, but not yet fully.

“More than half of all the aluminium currently produced in the European Union (EU-27) originates from recycled raw materials and that trend is on the increase.” This message in Chapter 7 of the report is really good news, especially since in a growing market, considering the use of Al in many long-lived product, 100% cannot be reached. As stated correctly, there is still enough opportunity to improve and thus decrease the overall energy demand. The Al-scrap remelting industry is fragmented, despite a consolidation leading to larger units, and data acquisition is not easy. The results obtained in co-operation with OEA (Organisation of European Aluminium Refiners and Remelters) are nevertheless trustworthy and rely on a robust Al-recycling material flow analysis published recently (Boin and Bertram 2005).

The co-operation with the European Reference Life Cycle Data System already resulted in two generic LCI datasets (aluminium sheet and profile), which are publicly available free of charge (Joint Research Center Ispra, <http://lca.jrc.ec.europa.eu>).

### 3.3.3 Additional information

Whereas the report is available as a freely downloadable PDF document with broad distribution, the full LCI datasets are available on request (EAA Brussels, [lci@eaa.be](mailto:lci@eaa.be)).

This information is supplied in the form of six excel data files. These files comprise:

- Primary aluminium 2005
- Aluminium sheet 2005

- Remelting and casting of clean aluminium scrap 2005
- Aluminium recycling 2005
- Aluminium foil 2005
- Aluminium extrusion 2005

These files are supplied in addition to the draft LCI reports. They will be indispensable for software suppliers for updating the data bases. In addition, internal EAA reports were made available during the critical review.

## 4 Confirmation by the reviewer

According to ISO 14040 (2006a)

“The critical review process shall ensure that:

- The methods used to carry out the LCA are consistent with the international Standard;
- The methods used to carry out the LCA are scientifically and technically valid,
- The data used are appropriate and reasonable in relation to the goal of the study;
- The interpretations reflect the limitations identified and the goal of the study;
- The study report is transparent and consistent.”

These five points can be confirmed with a few restrictions discussed in the previous sections. With regard to the first item, consistency with ISO 14040/44, there is a formal lack of a section ‘interpretation’ indicated above. It has also been discussed above that the study is not a full LCA, but the standard allows for LCI studies. As such, the study conforms to ISO.

The methods used in data collection and modelling are described clearly and correspond to the state of the art. They should be published (see also Leroy 2009) and become standard for generic data collection.

The third item (data) is the heart of the study, the data used in addition to the original data stem from one of the leading software systems. Additional data not shown in this report are made available to interested persons (see Section 3.3.3).

The interpretation is in accordance with the restricted scope and refers to the representativity and quality of the original data. Although not statistically analysed, the user can be sure to have the best possible dataset for Al in Europe. In the future, there may be a greater demand for statistically analysed data in order to perform error calculations and uncertainty analysis (Ciroth 2004, 2008; Heijungs and Frischknecht 2005); this may lead to higher expectations with regard to the primary data deliverers.

Finally, the report is transparent and consistent. It is clearly written and well illustrated. The full critical review report (Klöppfer 2008a) is included as an annex to the LCI data report (EAA 2008).

## 5 Summary and recommendations

To sum up, the EAA LCI Project (EAA 2008) is an excellent example for generic data acquisition, consolidation and presentation. It contributes to the LCA development by providing reliable data for one important material and the related most important semi-finished products and continues a tradition of more than a decade in an exemplary way.

Possible improvements for the next round have been identified, specifically

- Including inventory data for land use (mining) and water consumption
- Improving the modelling of solid waste treatment in LCI
- Improving the consistency with ISO structure (component Interpretation)
- Continue and extend the co-operation with the EU-LCA data base
- Extend the analysis toward life cycle sustainability assessment
- Contribute to enhancing the recycling
- Contribute to further reduction of heavy oil use in alumina production.

The last two items surpass the direct influence of the LCI team but address the relevant industries and administrations. Life cycle methods can neither replace nor enforce management decisions. They can, however, inform, educate and lead to new ideas and enhanced decision making. A comparison of results given by the latest report (EAA 2008) with the previous ones (EAA 2000, 2005) shows that improvements of the environmental performance via small steps have still been possible. No radical improvement, however, seems to be possible in that way. It is therefore proposed to rethink the whole aluminium system including renewable energy (e.g. solar energy) and explore possible new production methods (e.g. the development of inert anodes, now in the research stage). Although the thermodynamic limits cannot be overcome, there is no reason not to invest in radically new innovation (a co-operation with the leading technical universities may help in this regard). LCA may act as a guide to prevent trade-offs.

**Acknowledgement** My thanks are due to Christian Leroy and Jörg Schäfer (both EAA), to Bernard de Gélas (expert consultant, Paris) and to Marlen Bertram (IAI, formerly OEA) for the good co-operation during the critical review.

## References

- Bertram M, Buxmann K, Furrer P (2009) Analysis of greenhouse gas emissions related to aluminium transport applications. *Int J Life Cycle Assess* 14(special issue 1). doi:10.1007/s11367-008-0058-0
- Boin UMJ, Bertram M (2005) Melting standardized aluminum scrap: a mass balance model for Europe. *JOM* 57(8):26–33
- Boustead I (1996) LCA—How it came about. The beginning in UK. *Int J Life Cycle Assess* 1(3):147–150
- Boustead I, Hancock GF (1979) Handbook of industrial energy analysis. Horwood, Chichester, UK
- Ciroth A (2004) Uncertainty in life cycle assessments. *Int J Life Cycle Assess* 9(3):141–142
- Ciroth A (2008) Fehlerrechnung in Ökobilanzen: Effiziente Kombination von Näherungsverfahren und Simulation. Vdm Verlag Dr. Müller (ISBN: 978-3836475136)
- Declaration by the Metals Industry on Recycling Principles (2007) *Int J Life Cycle Assess* 12(1):59–60. doi:http://dx.doi.org/10.1065/lca2006.11.283
- EAA (European Aluminium Association) (2000) Environmental profile report for the European aluminium industry. EAA, Brussels
- EAA (European Aluminium Association) (2005) Environmental profile report for the European Aluminium Industry. Primary aluminium update—Year 2002; semi-finished aluminium products and process scrap recycling update—Year 2002; aluminium recycling in LCA. EAA, Brussels
- EAA (European Aluminium Association) (2008) Environmental profile report for the European Aluminium Industry. Life Cycle Inventory data for aluminium production and transformation processes in Europe. Brussels, April 2008, 72+12 pp
- Fava J, Pomper S (1997) Life-cycle critical review! Does it work? Implementing a critical review process as a key element of the aluminium beverage container LCA. *Int J Life Cycle Assess* 2(3):144–153
- Frees N (2008) Crediting aluminium recycling in LCA by demand or by disposal. *Int J Life Cycle Assess* 13(3):212–218
- Gatti JB, de Casthilo Quieroz G, Corrêa Garcia EE (2008) Recycling of aluminium can in terms of life cycle inventory (LCI). *Int J Life Cycle Assess* 13(3):219–225
- Guinée JB, Heijungs R, Huppes G (2004) Economic allocation: examples and derived decision tree. *Int J Life Cycle Assess* 9(1):23–33
- Heijungs R, Frischknecht R (2005) Representing statistical distributions for uncertain parameters in LCA. Relationships between mathematical forms, their representation in EcoSpold, and their representation in CMLCA. *Int J Life Cycle Assess* 10(4):248–254
- Hunkeler D (2006) Societal LCA methodology and case study. *Int J Life Cycle Assess* 11(6):371–382
- Hunkeler D, Lichtenvort K, Rebitzer G (2008) Environmental life cycle costing. CRC, Boca Raton, Florida
- International Standard (ISO) (2006a) Environmental management—life cycle assessment: principles and framework. ISO 14040
- International Standard (ISO) (2006b) Environmental management—life cycle assessment: requirements and guidelines. ISO 14044
- International Standard Organisation (1997–2000) Environmental management—life cycle assessment ISO 14040-14043
- Jørgensen A, Le Bocq A, Nazarkina L, Hauschild M (2008) Methodologies for social life cycle assessment. *Int J Life Cycle Assess* 13(2):96–103
- Klöpffer W (1997a) In defence of the cumulative energy demand. *Int J Life Cycle Assess* 2(2):61
- Klöpffer W (1997b) Peer (expert) review according to SETAC and ISO 14040. Theory and practice. *Int J Life Cycle Assess* 2(4):183–184
- Klöpffer W (2005) The critical review process according to ISO 14040–43: an analysis of the standards and experiences gained in their application. *Int J Life Cycle Assess* 10(2):98–102
- Klöpffer W (2006) The role of SETAC in the development of LCA. *Int J Life Cycle Assess* 11(Special Issue 1):116–122
- Klöpffer W (2008a) Critical review report. In: Environmental profile report for the European Aluminium Industry. Life cycle inventory

- data for aluminium production and transformation processes in Europe. European Aluminium Association (EAA), Brussels, April 2008, p 12
- Klöpffer W (2008b) Life cycle sustainability assessment of products. *Int J Life Cycle Assess* 13(2):89–94
- Leroy C (2009) Provision of LCI data in the European aluminium industry: methods and examples. *Int J Life Cycle Assess* 14 (special issue 1). doi:[10.1007/s11367-009-0068-6](https://doi.org/10.1007/s11367-009-0068-6)
- Milà i Canals L, Bauer C, Depestele J, Dubreuil A, Freiermuth Knuchel R, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007) Key elements in a framework for land use impact assessment within LCA. *Int J Life Cycle Assess* 12(1):5–15
- SETAC (Society of Environmental Toxicology and Chemistry) (1993) Guidelines for life-cycle assessment: a ‘code of practice’. In: SETAC Workshop, Sesimbra, Portugal, 31 March–3 April 1993, 1st edn, Brussels and Pensacola (Florida), August 1993
- SETAC (Society of Environmental Toxicology and Chemistry) (2008) Life cycle costing, a code of practice. Presented by Hunkeler D 5th SETAC World Congress, Sydney
- VDI 4600 (1997) Kumulierter Energieaufwand (Cumulative Energy Demand). German and English. VDI-Gesellschaft Energietechnik Richtlinienausschuß Kumulierter Energieaufwand, Düsseldorf
- Werner F, Richter K (2000) Economic allocation in LCA. A case study about aluminium window frames. *Int J Life Cycle Assess* 5(2):79–83